FIRST OUTDOOR POSITIONING RESULTS WITH REAL GALILEO SIGNALS BY USING THE GERMAN GALILEO TEST AND DEVELOPMENT ENVIRONMENT – GATE

G. Heinrichs, E. Löhnert, and E. Wittmann, IfEN GmbH, Germany
R. Kaniuth, Institute of Geodesy and Navigation, University FAF Munich, Germany

OVERVIEW

Currently the Galileo Test and Development Environment GATE is being built up in southern Germany by a consortium of several German companies and institutes on behalf of the German Aerospace Center (DLR) with funding by the German Federal Ministry of Education and Research.

The performance tests regarding the user positioning performance will cover various test scenarios for static and dynamic cases. The tests will be performed in all available GATE operation modes with GATE signals only and in combination with GPS. Preliminary test during system testing phase showed already impressive positioning performance with dedicated signals and services.

The paper gives an overview on the variant test scenarios and setups and illustrates the detailed hardware setup. An introduction in the GATE Backend Receiver Software, which computes the position solution, is presented. It describes the test procedures and shows the test results. Finally an evaluation on the different GATE services with respect to the positioning performance is presented.

1. INTRODUCTION

GATE is a ground-based realistic test environment for developers of receivers, applications and services for the future satellite navigation system Galileo. GATE is currently being built-up and as from beginning of October 2007 - several years before Galileo becomes fully operational - Galileo signals will be emitted by 6 earth-fixed transmitters in the area of Berchtesgaden, located in the southeast of Germany in the German Alps. This will provide the opportunity for receiver, application and service developers to perform realistic field-tests of hardware and software for Galileo at an early stage. In this way GATE will also support German and European products for Galileo entering the market. GATE is currently in the experimental operation phase, which will lead to full operational capability (FOC) end of September 2007.

While the motivation of the US ground-based ranging test bed Yuma in the 70's was to prove the concept of satellite navigation, no one doubts that Galileo will work from a conceptual point of view. However, it is still an ambitious technological project, introducing a signal structure far more sophisticated than the GPS C/A Code. In fact there are three major mission objectives to be covered by GATE – Signal Experiments, Receiver Testing and User applications.

2. GATE INFRASTRUCTURE & TEST AREA

2.1. GATE System Architecture

FIG. 1 gives an general overview of the system architecture of the GATE infrastructure.

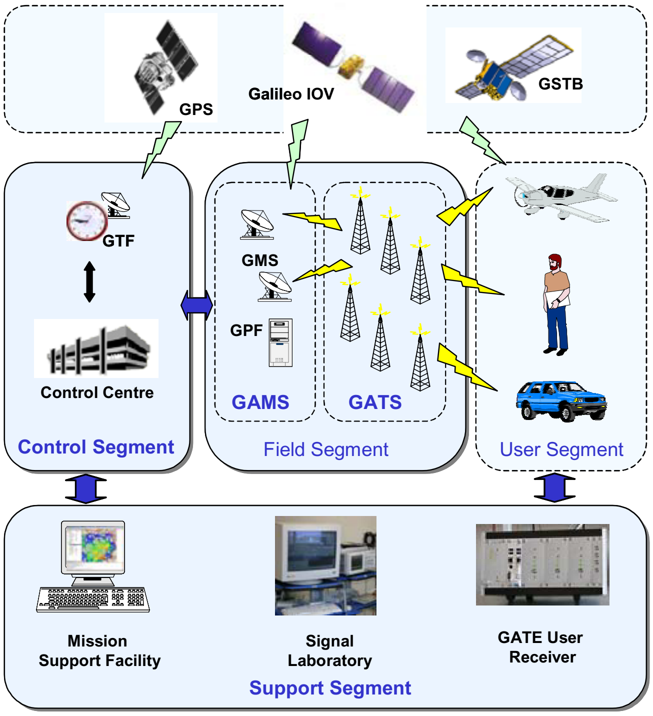

FIG 1. GATE Infrastructure Overview

Differing from real (navigation) satellite missions a differentiation of the GATE system into the typical sectors Space Segment, Ground Segment and User Segment is not adequate. A division of the GATE system into the following four segments was considered to be more appropriate:

- The Transmit Segment (GATS), consisting of six earth-fixed GATE Transmit Stations enclosing the service area.
- The Mission Segment (GAMS), consisting of two GATE Monitoring Stations (GMS) and the GATE Processing Facility (GPF) located within the test area. The GPF provides real-time estimation of the system parameters (e.g., transmitter clocks), generates navigation messages, steers the signal generators, and sustains the "virtual constellation and environment."
- The Control Segment (GCS) includes the GATE Monitoring & Control Facility (GMCF), the GATE Ar-

chiving & Data Server (GADS), and the GATE Time Facility (GTF).

- The Support Segment comprising the facilities and functionalities for preparing and supporting the GATE missions. These are in particular the mobile GATE User Terminal (GUT) with the user receiver, the GATE Mission Support Facility (GMSF), and the GATE Signal Laboratory (GSL).

The ground-based transmitters, which are part of the GATE Transmit Segment (GATS), will emit all frequencies foreseen for Galileo. Therefore they have to be flexible in signal generation and adaptive to changes in signal structure. As GATE is a real-time system it is necessary to feed the navigation message in real-time to the transmitters. They are also equipped with stable atomic clocks. The following FIG. 2 shows the six envisaged transmitter locations, as well as the transmitter rack and the corresponding transmit antenna.

FIG 2. GATE Transmitter Locations and Transmitter Rack GATE Infrastructure Overview

The GATE Signal Generators developed by Astrium GmbH are designed to generate simultaneously the Galileo navigation signals in the E5, E6 and L1 band. As shown on the left photo in FIG. 2, its major building blocks are the Control Computer, a Rubidium Reference Clock Unit and three (mostly identical) Signal Generation Units, one for each Galileo frequency band, followed by an RF amplifier section. With exception of the Voltage controlled Oscillator (VCO) for the generation of the RF carrier frequency, the Signal Generation Units are based on identical hardware providing a high degree of freedom to be configured by software according to the different channel setup requirements.

The GATE Mission Segment (GAMS) monitors the navigation signals by using two GATE Monitoring Stations (GMS), performs the time synchronisation of all system clocks and generates navigation messages and steering commands to be sent to the six transmitters. The tasks denoted above are mainly performed by the two GAMS core elements, the GATE Processing Facility (GPF) and the GATE Monitor Receiver (GMRx), both developed by IfEN GmbH.

The GATE Control Segment (GCS) includes all the functionality and facilities that are required for the mission control and operation. The main tasks it has to perform are to monitor and control the entire GATE system, to host and operate the control centre, which serves as operational node of GATE including e.g. the mission planning, to host and provide the GATE system time, and to archive the GATE mission data.

The main tasks of the GATE Support Segment (GSS) finally comprise the appropriate preparation, i.e. simulation and planning, of the GATE experiments with dedicated software tools, as well as the provision of the GATE User Terminals equipped with a combined Galileo/GPS receiver.

2.2. GATE Test Area Berchtesgaden / Germany

The GATE test area is located in the region of Berchtesgaden in the very south-eastern part of Germany / Bavaria. The service area is depicted in the maps shown in FIG. 8 below. The GATE test area, which is roughly limited by the imaginary connection lines between the signal transmitters, has a size of about 65 km², while the GATE core test area, as marked in FIG. 3 below on the right hand side, is about 25 km². The two monitoring stations are located at an exposed position quite centric within the GATE test area. As it can be seen from FIG. 3 below, Berchtesgaden is surrounded by high mountains rising up to over 2000 m. The establishment of the GATE transmitters on well exposed positions allows for the emission of the GATE signals with average elevation angles between 10 to 15 degrees from a user's point of view located within the GATE test area.

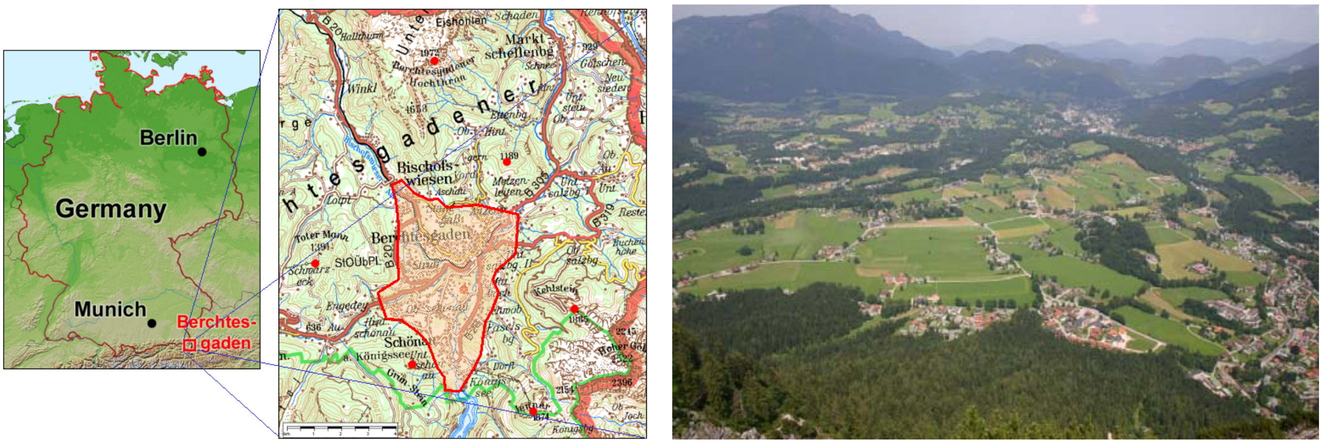

FIG 3. GATE Service Area Berchtesgaden / Germany (core test area marked in red, transmitters marked as red dots) and view into the GATE test area

Five GTSs will be set up using already existing infrastructure, e.g. TV or mobile phone masts. Additionally, only one completely autonomous GTS has to be established. Within this context, the German Regulatory Authority for Telecommunications and Posts (RegTP) has already approved the usage of the requested frequency bands E5a/b, E6 and L1 for the transmission of the GATE signals in the area of Berchtesgaden.

2.3. GATE Field Installation

With the set-up of the autonomous station at the mountain Gruenstein the in-field installation of the testbed has recently been started. The container for accommodating the transmit equipment was installed by helicopter at a location close to the mountain top. The solar panels for the autonomous power supply were finally mounted on the top of the container. FIG. 4 shows the GTS container with the view into the valley.

FIG 4. Transmit Station at the Gruenstein mountain and Helicopter transport of GTS rack

The first two transmit units were installed subsequently at the locations Gruenstein and Stoehrhaus. First tests of remotely accessing and controlling the transmit station were performed successfully. The set up of the transmit equipment on the remaining stations has taken place in January and February 2007.

3. THE GATE/GALILEO RECEIVERS

The GATE user terminal consists of the receiver itself and the user interface that is in fact a Panasonic Toughbook with touch screen TFT display. The user interface and the receiver communicate via Ethernet cable over UDP protocol. The navigation processing and visualization is done on the user interface, shown in FIG. 5.

The GATE user terminal is a three-frequency GPS/Galileo receiver that covers GPS L1, Galileo L1, Galileo E5a and E5b and Galileo E6 positioning. Since there is still no definition of the Galileo E6 CNAV navigation message content, positioning with E6 is currently not possible. For Galileo/GATE L1 and or E5b positioning the Galileo/GATE INAV message is used. For Galileo/GATE E5a positioning the FNAV message is used. In the actual development stage the navigation software processes each frequency on its own, except of reasonable ionosphere free linear combinations like Galileo/GATE L1 and E5a or L1 and E5b. The latter frequency combination benefits from the fast I/NAV message transmission via both frequencies and leads to a position fix after minimal 15 seconds and maximal 29 seconds, after acquisition of signals from at least three transmitters/satellites was achieved. The navigation software also provides various logging capabilities for data post processing. Additional the GATE User Terminal provides NMEA position message output via serial COM port.

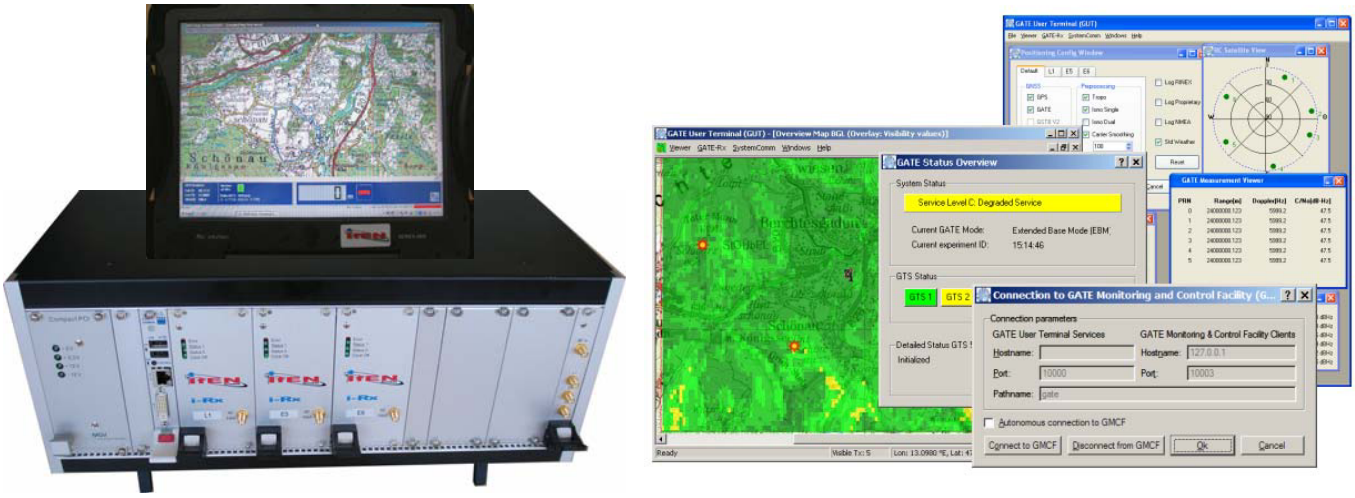

FIG 5. GATE User Terminal and its User Interface

The algorithm used for position estimation is an epoch-by-epoch standard least-square adjustment, because this yields to unfiltered position estimates and therefore unpolished performance results. The GATE User Terminal Software (GUT-SW) differs to other GNSS positioning software packages in that way, that different navigation message data streams have to be handled. For GPS positioning we have the normal GPS navigation message bitstream, also in the GATE Virtual Satellite Mode (VSM), where the navigation message is based on the Galileo navigation message. In GATE Base Mode (BM) and Extended Base Mode (EBM) is content of the navigation message is different, because there we have satellites/transmitters located on the earth. These locations cannot be described by the elements of Kepler and therefore the navigation message content had to be changed. The mode of operation of the GATE system is detected by a synchronization word in the navigation message, so that the GUT-SW can switch to the adequate navigation message-decoding module.

While in standard GPS positioning scenarios the centre of the earth as best guess for the users a-priori position, is sufficient to make the position solution converge to the correct solution, this will not work in GATE BM and EBM modes. The reason for this is the small-sized area of GATE. To make the position solution converge in GATE BM and EBM the approximate user position has to be known better than 50m in horizontal position and 10-5m in vertical position. The closer the user comes to the height of the lowest transmitter the worse is the height accuracy and the better the users approximate height has to be known. Therefore the GATE user equipment contains an external GPS Bluetooth receiver, which is typically a SIRF III GPS mouse, to feed the GUT-SW's positioning algorithm with a-priori coordinates. This external GPS receiver also enables the user on the flight comparison between the GPS estimated position and the position estimated with GATE/Galileo signals.

Due to the very low elevation angles, not exceeding 15°, of the transmitters seen by the user in the GATE service area and the corresponding degradation of height accuracy, the GUT-SW additionally provides a 2-D positioning mode. In 2-D positioning mode the users height is fixed, which in fact means that the users height is set to the height estimated by the external GPS mouse. This 2-D positioning mode is automatically switched on, when only three transmit stations are visible and therefore improves the position availability for the GATE user.

Furthermore a special correction algorithm for the tropospheric delay in GATE BM and EBM is implemented.

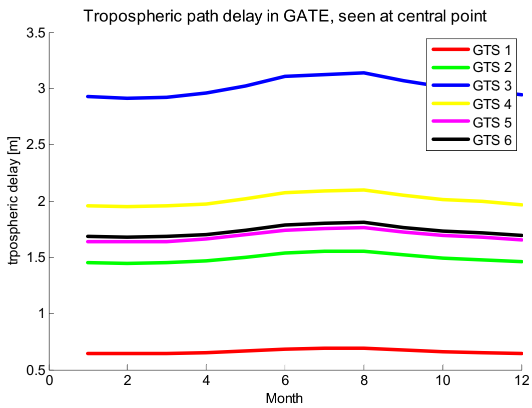

FIG 6. Tropospheric path delay as senn from GATE central point to the GATE transmitters

FIG. 6 shows the theoretical (model based) tropospheric path delay to the six GATE transmit stations seen from the GATE central point over a 12 month period. The monthly base data for temperature, humidity and pressure for this model are mean values over several years from a local weather station. Of course the user can enter actual weather data via the graphical user interface of the GATE user terminal software. The blue line denotes the tropospheric path delay to GTS-3, which more than four times farther away from the GATE central point than GTS-1 (red line). The delay variations during a year are about 10% with a maximum of about 0.3m. That yields to the conclusion that tropospheric delay correction with averaged weather data should be sufficient.

4. POSITIONING PERFORMANCE IN THE GATE TEST AREA

The positioning performance tests presented in this article consists of static positioning tests at the GATE monitoring station on all available frequencies and combinations as well as static and dynamic positioning tests in the GATE area near the GATE central point in the middle of the service area. The positioning tests at the GATE monitoring station were performed with the GATE monitor receiver that contains a rubidium clock. The positioning tests in the GATE area were carried out with the GATE user receiver light. This light version of the user receiver only holds base-band processing boards for L1 and E5 frequency.

The GNSS antennas at the GATE monitoring station are mounted on a quite big transmitter pylon, operated by the "Bayerischen Rundfunk", which is shown in FIG. 7.

One can easily see, that the pylon is overfilled with transmitting antennas from various radio stations and mobile communication networks. The impact of these transmitting antennas can be seen by comparing a GPS only positioning solution from an antenna situated on the roof of the IfEN company building in Poing/Munich and a GPS only positioning solution from the GATE monitoring antenna mounted on the pylon. This comparison is illustrated in FIG. 8.

FIG 7. Tropospheric path delay from GATE central point to the GATE transmitters

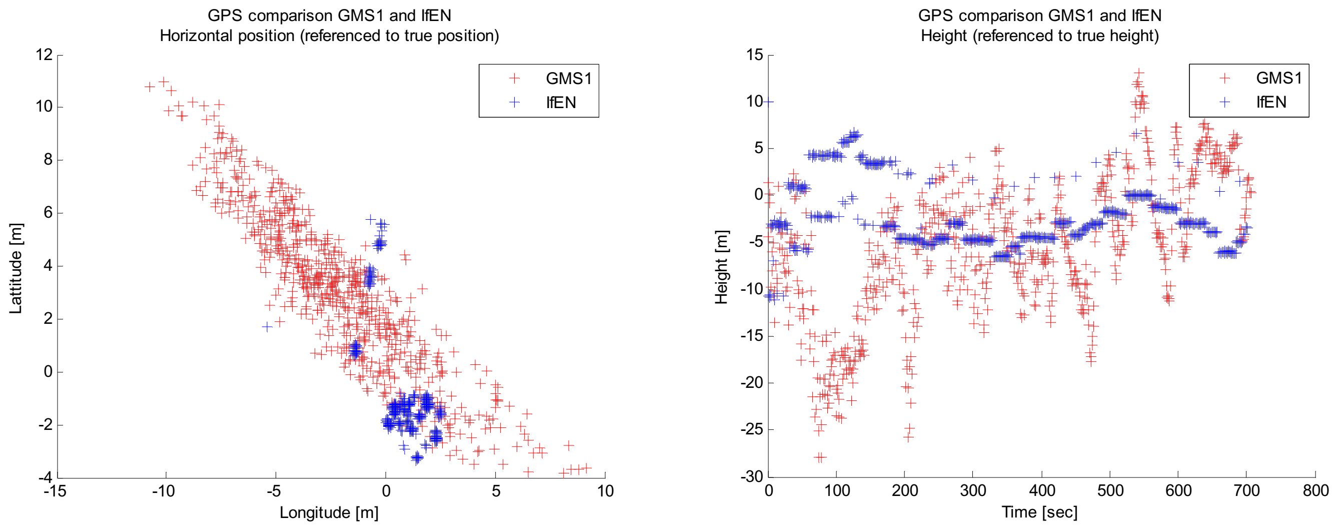

FIG 8. Comparison of GPS position estimates at the GATE monitoring station (red crosses) and IfEN's roof antenna in Poing (blue crosses)

The red crosses on the left viewgraph denote the GPS position estimates at the GATE monitoring antenna, while the blue crosses denote the GPS position estimates at the IfEN roof antenna in Poing. Both position estimates are refenreced to their true positions. For both experiment the Gut Software was used for positioning, ionospheric and tropospheric correction were switched of and no carrier smoothing was applied. While the position estimates from the IfEN roof antenna show a little scattering around the true position the scattering at the GMS1 antenna is much bigger. The standard deviation of the position estimates is about 2.07m for the IfEN position and 4.51m for the GMS1 position. The right viewgraph shows the height estimates at both stations. Here also the estimates at the GMS1 station is much more noisy than the ones at the IfEN antenna. Also the number of tracked satellites differed between the GMS1 location and the IfEN antenna location. While at the IfEN roof antenna the GATE receiver tracked eight GPS satellites in average, the GATE receiver at the GMS1 antenna only tracked four GPS satellites. This leads to the conclusion that the transmitting antennas on the pylon, shown in FIG. 7, have much more influence on the GNSS signal quality then assessed.

The following tests cover static positioning at the GATE monitoring station (GMS1) on GATE/Galileo frequencies L1 and E5a. For this test the GATE monitoring receiver, which is connected to the GATE monitoring antenna was used. An external rubidium clock clocks the monitor receiver. The left plot in FIG. 9 shows the horizontal position scattering around the true GMS1 position, which is around +-10m lateral and longitudinal which is at the accuracy level of the GPS position estimates shown in FIG. 8. As described before, the height accuracy in GATE BM and EBM is worse than for GPS or GATE VSM mode. This underlines a VDOP value of about 14.7 at the GMS1 location. The right viewgraph of FIG. 6 shows the difference of the height estimates on L1 and E5a referenced to the true height of GMS1. It can be noticed, that the variation of the height estimates from L1 observations are slightly smaller than the ones from E5a observations. This fact has to be clarified because from the performance point of view, the E5a signal should be better than the L1 signal.

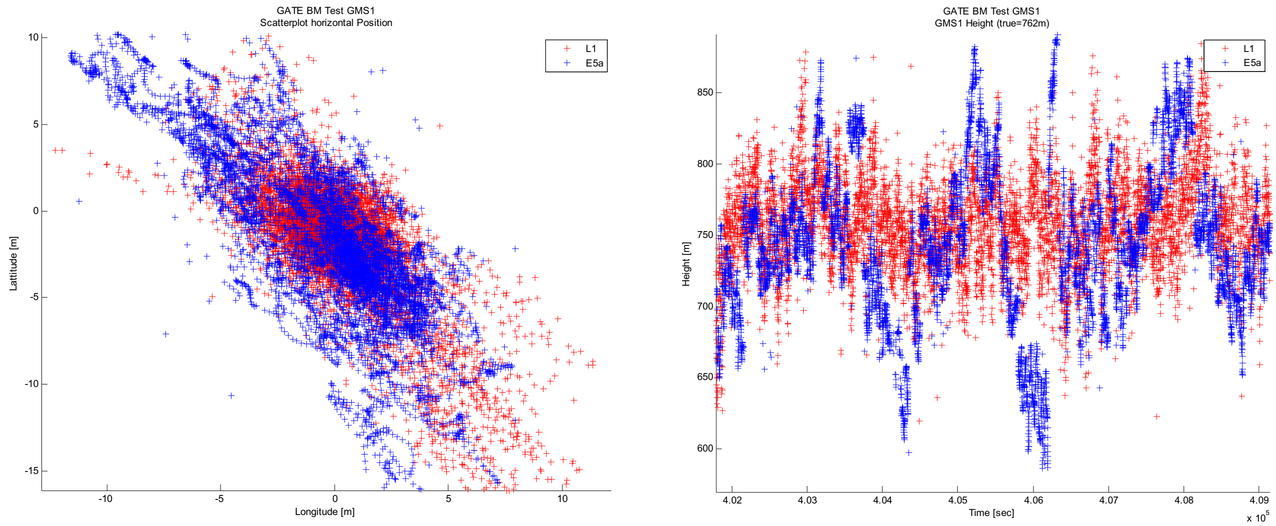

FIG 9. Comparison of position estimates with L1 (red crosses) and E5a (blue crosses) at the GATE monitoring station GMS1

At the GATE central point all transmit stations (GTS) are visible and HDOP and VDOP values are best for the GATE service area. Therefore the positioning accuracy should be best in the vicinity around the GATE central point. FIG. 10 shows the positioning performance at the GATE central point for a static receiver. For this experiment the light version of the GATE user receiver was used. This light version of the GATE receiver only has L1 and E5 base-band processing and an internal TcXo clock. It was installed in a van with the GATE user antenna on the top of the van. The left viewgraph in FIG. 10 shows the proportion of the GATE central points location. First the van was parked beside the road in the meadow heading north. After a while the van turned to south direction by moving forth and back. After turning into south direction the dynamic test started which is described later on. At still stand the position scattering is about +-5m in both directions, which is a quite good performance. It must be pointed out, that no buildings shade or reflect signals in the near vicinity of the central point. This can also be seen in the right picture of FIG. 10.

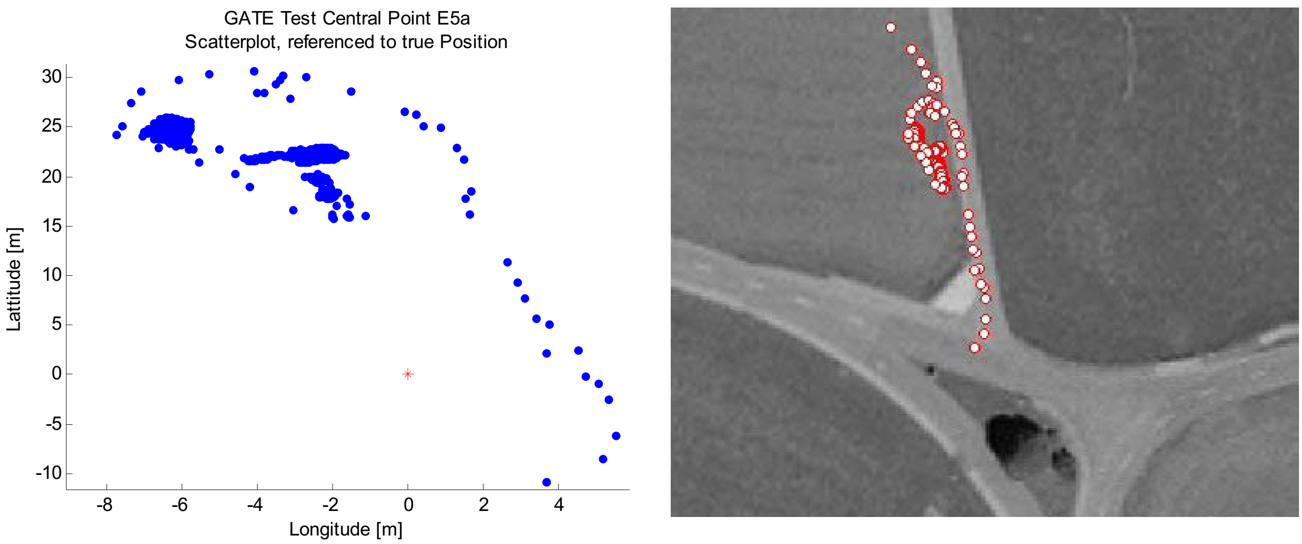

FIG 10. Position estimates with E5a in BM at the GATE central point

The experiment illustrated in FIG. 10 was repeated in the GATE VSM mode, where the GATE/Galileo signals are simulated as they were transmitted from orbiting satellites. In fact of course the signals are transmitted by the earth fixed transmitters, so that signal fading and multipath effects, due to building and the landscape, are still present.

The result of the VSM mode experiment is shown in FIG. 11. The positioning accuracy is comparable with the one from FIG. 10.

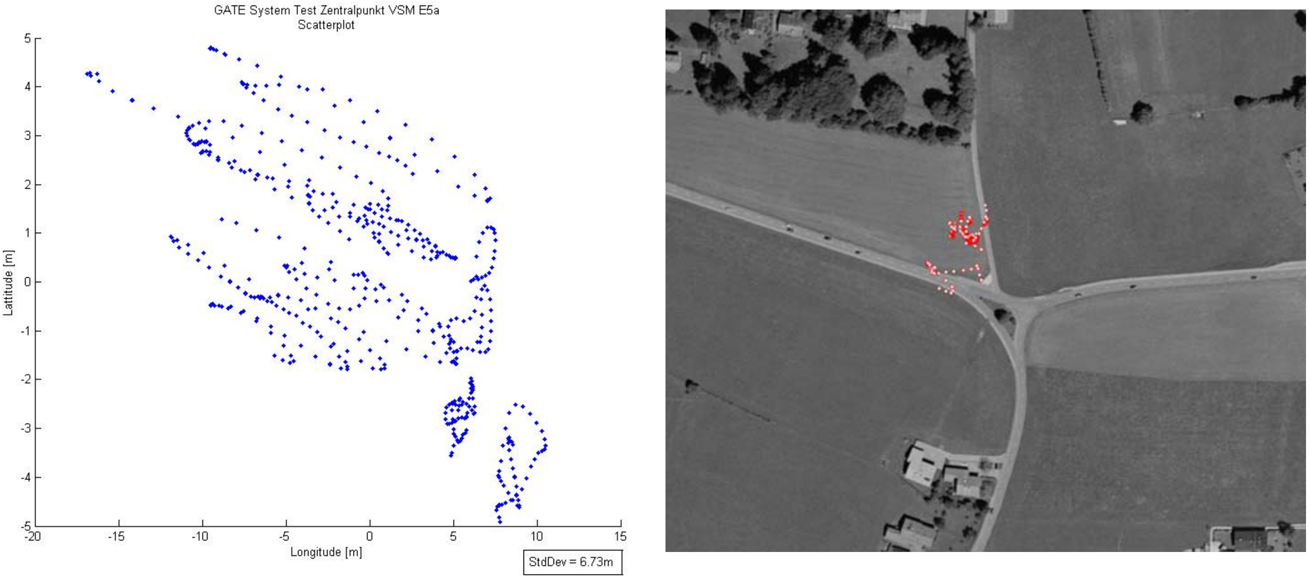

FIG 11. Position estimates with E5a in VSM at the GATE central point

Finally a preliminary dynamic positioning test was performed with the E5a signal in EBM operation mode, where the signal strength is steered dependent on the users location to have good carrier to noise ratio. This test started at the GATE central point, marked as (1) in FIG. 12. The red dots denote the estimated positions.

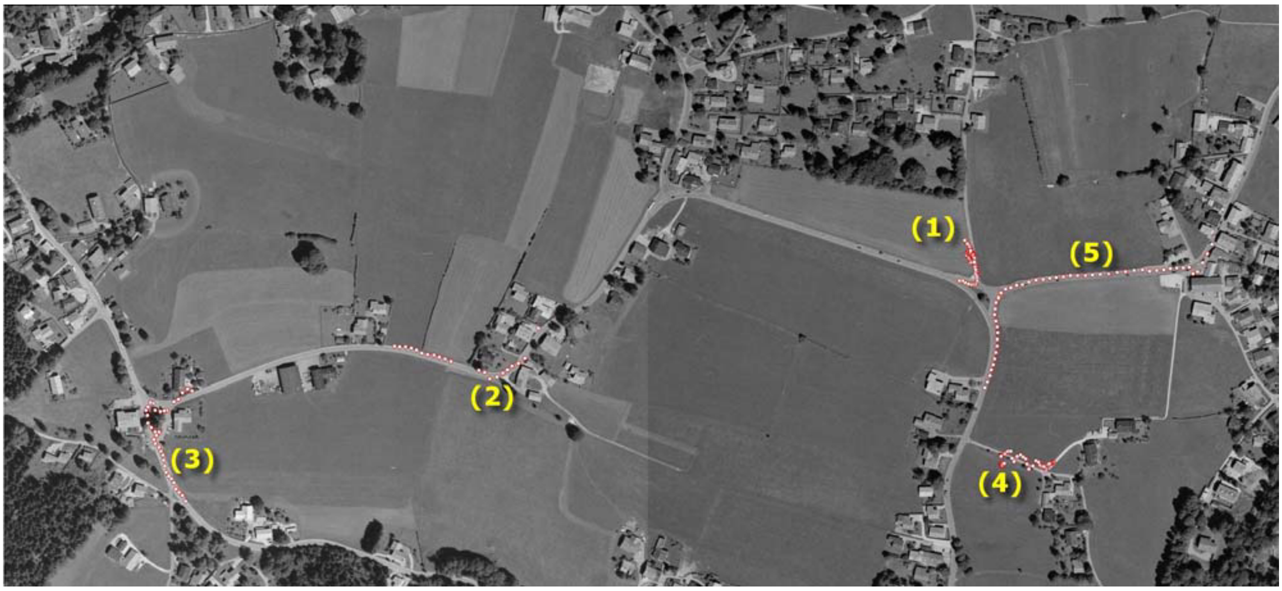

FIG 12. Position estimates with E5a in EBM at the GATE central point

After several minutes at the central point the test vehicle turned right into west direction at the crossing close to the central point. Shortly after turning in west direction a big bus passed by and three of five signals were lost. Intensive analysis of the data from this test showed that signal fading and multipath cause most of these signal losses. These negative effects on the signals are founded by the low elevation of the transmit stations and thus reflections on the ground and the users surrounding objects. At the point marked as (2) in FIG. 12 the receiver reacquired the signals to 4 GTS and positioning went on until a new signal loss. Especially at section (3) and (5) the high accuracy of the position estimation can be seen, where no objects intercept the signal reception.

To become a feeling of the influence of the multipath effect on the position accuracy and availability of a position solution, a special experiment was performed, where the bottom of the GNSS antenna (Roke-Manor prototype antenna) was mounted inside a metal tube with a kind of ground-plane on the top of the tube to minimize the entering of multipath signals into the antenna. Several experiments were performed with different positions of the antenna inside the tube. The photos in FIG. 14 show the antenna in two different positions concerning the distance between the antenna phase centre and the metal plate.

FIG 13. Photos of the Roke-Manor prototype antenna inside the metal tube

In all experiments the same route was driven and the GATE EBM operation mode was used, where the power levels are steered according to the users position to have adequate signal strength for good tracking performance. The results of two of those experiments are illustrated in FIG. 15, while the left picture corresponds to the high antenna position (left photo in FIG. 14) and the right picture corresponds to the low antenna position above the metal plate (right photo in FIG. 14).

FIG 14. Position solutions (red dots) with using different antenna assemblies

The photos in FIG. 15 show the improvement of position availability and repeatability by using a multipath limiting installation of the GNSS antenna in the GATE area. These results underline the assumption a multipath limiting antenna design could considerably improve the positioning performance in the GATE test area.

5. FUTURE WORK

From a potential GATE user point of view the availability of a position fix is insufficient during the dynamic test shown in FIG. 12. Further investigation will be performed to improve the receiver's robustness against signal degradation due to multipath and fading. Also the positioning software could be modified to aid the receiver's signal processing.

6. CONCLUSIONS

GATE is a terrestrial test environment for developers of Galileo (Galileo/GPS) receivers, applications and services. It is currently being built-up in the region of Berchtesgaden/Germany and will be operational from autumn 2007. GATE is considered to be a necessary intermediate step for Galileo from laboratory into orbit in terms of realistic RF signal transmission. It will not only support signal validation by providing valuable data but provide insight in building a ranging system, simply by building it. This contributes to mitigate risks in the development of Galileo.

GATE will provide the opportunity for receiver, application and service developers to perform realistic field-tests of hardware and software for Galileo at an early stage, i.e. several years before the full operability of Galileo. And last but not least, GATE will allow full end-to-end testing of unmodified / commercial Galileo receivers. For further information on GATE please refer to the official project homepage http://www.gate-testbed.com.

7. ACKNOWLEDGMENTS

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